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Add sections on material attractiveness, NAS spent fuel standard, threat evolution.

Material Attractiveness

Proliferation Pathway Stages

Cleary [2007] divides the *proliferation pathway* into *stages*: diversion, facility misuse, transportation, transformation, and weapons fabrication. King [2010], using Cleary's methodology, compares a deep-burn fusion-driven blanket containing weapons-grade plutonium with a PWR burning MOX fuel enrichments of 5-9%. King [2010] considers the *stages* of theft, transportation, transformation, and nuclear explosive fabrication.

In the current study of used fuel storage security, a similar approach is appropriate. First, one must consider the *adversary's objective*, which can be categorized as *on-site radionuclide dispersion*, theft of material for *later radionuclide dispersion*, and theft of material for *later processing and fabrication into a nuclear explosive*.

For *on-site radionuclide dispersion*, only a single *proliferation pathway stage* is appropriate: dispersion. That situation will be addressed in future reports.

For *later radionuclide dispersion*, the *stages* are theft (by an outsider or by facility misuse by an insider), transportation, and transformation (from oxide spent fuel containing both fission products and actinides to a material size and shape suitable for dispersion).

For *later processing and fabrication into a nuclear explosive*, the *stages* are theft (by an outsider or by facility misuse by an insider), transportation, transformation (from oxide spent fuel containing both fission products and actinides to a metal alloy), and fabrication (of the alloy into a weapon). It should be noted that the theft and transportation *stages* are similar, and possibly identical, for *later radionuclide dispersion* and *later processing and fabrication into a nuclear explosive*.

Each *stage* can be evaluated separately, and the methodology can vary for each *stage*. For example, King [2010] starts with the methodology of Cleary for the theft, transportation, transformation, and fabrication *stages*. Then, for each *stage*, King [2010] assembles and modifies the attributes and inputs suggested by Cleary.

In the theft (also known as diversion) *stage*, Cleary [2007] has five high-level categories (material handling during diversion, difficulty of evading detection by the accounting system, difficulty of evading detection by the material control system, difficulty of conducting undeclared facility modifications for the purpose of diverting nuclear material, and difficulty of evading detection of the facility modifications for the purposes of diverting nuclear material). Each category has one or more subcategories. For example, the first category includes mass per significant quantity (SQ) of nuclear material, volume/SQ of nuclear material, number of items/SQ, material form (solid, liquid, powder, gas), radiation level in terms of dose, chemical reactivity, heat load, and process temperature. King [2010] adds the following two subcategories to that list: SQs available for theft, and interruptions/changes (normal and unexpected) in material stocks and flows. For the situation of an orphaned surface storage facility, this approach is applicable, with some of the categories and subcategories being modified to reflect the static situation (no additions or removals of fuel or containers). In addition, theft would require opening a large overpack and either removing a full container or opening that sealed container and then removing one or more spent nuclear fuel assemblies. These activities would require time without observation (detection), heavy-duty equipment, and some degree of protection of the thieves from radiological dose.

In the transportation *stage*, Cleary [2007] has two high-level categories (difficulty of handling material during transportation, and difficulty of evading detection during transport). Each category has a number of subcategories. For the situation of an orphaned surface storage facility, these categories are applicable.

The transformation *stage* of Cleary [2007] has three high-level categories (facilities and equipment needed to process diverted materials; knowledge, skills, and workforce needed to process diverted materials; and difficulty of evading detection of transformation activities). Again, there are subcategories. King [2007] adds a fourth high-level category: time required to transform the materials. For the situation of an orphaned surface storage facility, the categories are applicable, but the evaluations of each category and subcategory will be significantly different for *later radionuclide dispersion* than for *later processing and fabrication into a nuclear explosive.*

The fabrication *stage* of Cleary [2007] has three high-level categories (difficulty associated with design, handling difficulties, and knowledge and skills needed to design and fabricate). King [2010] replaces the first two high-level categories with the *Figure of Merit for Nuclear Explosives Utility* (FOM), with subcategories of bare critical mass, heat content of transformed material, dose rate of transformed material, and SQs available for theft. The next section of this report describes the FOM in more detail.

Material Attractiveness: Figure of Merit

Material attractiveness is a metric that describes the weapons utility of processed (transformed) nuclear material, for safeguards and security purposes, in an unclassified environment. Material attractiveness is a calculated number, a Figure of Merit, or FOM [Bathke, 2009a; Bathke, 2009b; Sleaford, 2010; King, 2010].

As shown in Equation 1, the FOM is defined [Sleaford 2010] as

Equation 1:

$$FOM = 1 - \log_{10}\left(\frac{M}{800} + \frac{M \bullet h}{4500} + \frac{N}{10}\left[\frac{D}{500}\right]^{\frac{1}{\log_{10} 2}} \right)$$

The FOM is an empirically derived formula that uses two physical parameters associated with the *product* material that is to be weaponized, i.e., the metal alloy produced in the transformation *stage* that is the starting point for the fabrication *stage*. These two parameters are the bare critical mass, M, in kg and the heat content, h, in W/kg. The third parameter in the equation is the dose rate, D, in rad/h; it could be calculated for the material *before or after transformation*, depending on what *stage* of the *proliferation pathway* is being evaluated. The term with the dose rate also includes the net weight of the item, N, in kg. The net weight for the theft *stage* would be the spent fuel assembly weight; whereas, the net weight for the fabrication *stage* is the weight of the component being handled.

The values of the constants and exponents in the FOM are designed to produce a range nominally between zero and three. FOM values less than 1.0 represent materials that are impractical for weapons utility (low or very low *Materials Attractiveness*, and *Attractiveness Levels D or E* from the DOE manual [DOE, 2006b]). FOM values greater than 2.0 represent materials preferred for nuclear explosive fabrication (high *Materials Attractiveness*, and *Attractiveness Level B* from DOE [2006b]). Intermediate values between 1.0 and 2.0 are potentially usable (medium *Materials Attractiveness*, and *Attractiveness Level C* from DOE [2006b]).

The argument of the logarithm of the FOM is the overall *complexity* of the material. Lower *complexity* increases the FOM due to the negative sign on the logarithm, and use of a logarithm converts large differences into a more comprehensible and manageable scale. The constant term from which the logarithm is subtracted is set to 1.0 so that the FOM is 1.0 when the material *complexity* is 1.0.

The first argument of the *complexity* is the *size factor*. It is based on M, the bare critical mass of the transformed material that is required to build a nuclear explosive. In general, as M increases, the required amount of source material increases. It becomes impractical to build the device when M becomes very large. The reference point for this impracticality has historically been set at 20% ^{235}U enrichment, which has a bare critical mass of about 800 kg. At the reference point, the *size factor* is 1.0 (leading to a zero logarithm and an FOM of 1.0 for that M when the other terms are ignored). An M of 80 kg (10x lower) would lead to an FOM of 2.0 when the other terms are ignored.

The second argument of the *complexity* is the *stability factor*. It is based on M and the heat content, h, in W/kg. The constant of 4500 W is based on radioisotope thermal generators (RTG), which use the decay heat of ^{238}Pu. An 80%:20% mixture of ^{238}Pu:^{239}Pu has M = 9.6 kg and h = 412 W/kg. At these values, the *stability factor* is 1.0, resulting in an FOM value of 1.0 for that heat content when the other terms are ignored. An 8%:92% mixture of ^{238}Pu:^{239}Pu has M = 10 kg and h = 43 W/kg (a *stability factor* 10x lower), resulting in an FOM of 2.0 when the other terms are ignored.

The third argument of the *complexity* is the *acquisition factor*. It is based on the acute dose rate, D, in rad/h. The dose rate used to evaluate the FOM should be consistent with the material at the *stage* of the *proliferation pathway* being considered. For the fabrication *stage*, it is the product material, whereas for the theft *stage* for an orphaned surface storage site, it is the spent nuclear fuel assembly. The dose rate is that at 1 m from the material, with no intervening shielding. The constant of 500 rad/hr is equivalent to 5000 rad/hr at a more realistic working distance of 30 cm for the fabrication *stage*. (For the theft *stage* in an orphaned surface storage site, we may need to change the constant to a higher value based on working with heavy equipment and being farther away from the material.) Nominally, 5000 rad results in 100% incapacitation within one hour and 50% incapacitation within 30 minutes. For D = 500 rad/hr, the dose rate multiplicative contribution to the *acquisition factor* is 1.0, resulting in an FOM value of 1.0 when the other terms are ignored. The exponent is designed to change the dose rate contribution by 10x (or the single-term FOM by 1.0) when the dose rate changes by 2x. For example, a dose rate of 250 rad/hr results in a single-term FOM of 2.0.

The *acquisition factor* is modified to account for the net weight, N, of the item in kg. The heavier or larger the item, the more difficult it is to steal or divert. A 10x change in net weight results in a change in FOM by one unit. For example, the single-term FOM is zero in the fabrication stage for a net weight of 100 kg and a dose rate of 500 rad/h. If the item is very small, or the net weight is not known, one can evaluate Equation 1 using N = M/5. A net weight constant of 10 kg is appropriate for the fabrication *stage*, but we may need to change the reference values of both the dose rate and the net weight for the theft *stage* at an orphaned surface storage site.

Material Attractiveness: Use in this Study

Nuclear weapons experts at both LANL and LLNL reviewed the FOM. While it was determined that there are a number of smaller factors that are not captured, it was agreed that the FOM adequately captures the dominant factors in an unclassified format.

The FOM represents an important part of the overall proliferation and security risks that are posed by various materials and processes in the nuclear fuel cycle. To contextualize the FOM, it overlaps strongly with one of the six proliferation resistance measures (Fissile Material Type) identified in the Proliferation Resistance and Physical Protection (PR&PP) methodology [DOE 2006c], and it overlaps strongly with the material attractiveness criteria which are a key part of the DOE graded safeguards table [DOE 2006b]. Therefore, in the case of proliferation resistance, there are five other factors that need to be considered (technical difficulty, cost, time, detection probability, and detection resource efficiency). In the case of physical protection, there are two other factors that need to be considered (material quantity and security category).

With the above background on *proliferation pathway stages* and the material attractiveness figure of merit, we can modify the figure of merit for the particular situation of an orphaned surface storage facility, for each of three potential *adversary objectives* (*on-site radionuclide dispersion*, theft of material for *later radionuclide dispersion*, and theft of material for *later processing and fabrication into a nuclear explosive*). For example, King [2010] aggregates the FOM in the nuclear explosives fabrication *stage* with the number of SQs available for theft in the two nuclear systems he compared (a fusion-fission hybrid system deep-burning Pu in the subcritical blanket and a PWR burning MOX). King multiplies the FOM by a function that has a value of 1.0 for SQs above about 1.5 and that has a value of 0.0 for SQs below about 0.5. This enabled the King study to show that, after 7 years of deep-burn irradiation time, the fusion-fission system is impractical to an adversary seeking to divert material for *later processing and fabrication into a nuclear explosive*.

The figure of merit, in turn, plays a role in the larger assessment of used fuel storage security being developed in this study. The modified figure of merit for each *proliferation pathway stage* and *adversary objective* is an integral part of the overall assessment. It can include some of the pertinent drivers and be integrated with other approaches to estimate other pertinent drivers.

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